Development of Acidic Flux for Submerged Arc Welding of Stainless Steel

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Abstract—*Submerged arc welding (SAW) is one of the most widely used processes for welding of low carbon steel, high strength low alloy steel, nickel-base alloys and stainless steel. A granular flux, which is used in submerged arc welding, plays an important role and it may cost up to 50% of the total welding consumable. The flux should provide the appropriate weld metal composition and exhibit good welding behaviour. These two requirements can be achieved by maintaining the flux ingredients within the optimum range. In the present research work the cost effective and high performance agglomerated flux is developed systematically and scientifically for the submerged arc welding of stainless steel. Taguchi's experimental design based on L9 orthogonal array was employed for conducting the experiments and analyzing the effect of process parameters (open circuit voltage, current and travel speed) on the bead geometry of the weld using developed flux in submerged arc welding process. The bead surface appearance was found to be excellent and free from any visual defects. The chemical composition of weld metal was within the acceptance range of AWS specifications.*

Keywords: *Submerged Arc Welding, Acidic flux, Taguchi method, Bead geometry.*

Introduction

Submerged arc welding process is one of the most widely used processes for fabrication of thick plates, pipes, pressure vessels, railroad tanks, ships, heat exchangers etc. It was invented simultaneously in U.S.A and U.S.S.R in 1930's. It contributes to approximately 10% of the total welding. Apart from joining, this process can also be used for overlaying applications to increase corrosion and wear resistance on the surface.

Submerged arc welding process is characterized by higher metal depositing rate, higher welding speed, higher process efficiency and lower hydrogen content in the weld metal [1,2,3,4,5]. This process is commercially suitable for welding of low carbon steel, high strength low alloy steel and stainless steel [6].

Flux plays an important role in deciding the weld metal quality. It influences the weld metal physically, chemically and metallurgically. Physically, it influences the bead geometry and shape relationships, which in turn affects the load carrying capacity of the weldment [7,8,9]. Chemically, it affects the chemistry of the weld metal, which in turn influences the mechanical properties of the weld metal [10,11,12,13]. Metallurgically, it influences the microstructure and hence again affects the properties of the weld metal [14,15]. The flux has several functions. It protects the weld metal from the atmospheric contamination, stabilizes the arc, provides the appropriate weld metal composition, deoxidizes the weld metal and influences the bead shape morphology [16,17,18,19].

In this research work it is tried to develop the cost effective and high performance agglomerated flux systematically and scientifically for the submerged arc welding of stainless steel. The effect of welding process parameter of voltage, current and travel speed on the bead geometry (bead width and bead height) has also been investigated.

For the prediction of the effects of welding parameters on the bead geometry, it is essential to generate the data by conducting the experiments according to the corresponding actual conditions of welding. The experiments should supply the required information with the minimum efforts, time and resources. Therefore, in order to perform the required experiments efficiently, the experimental plan must be designed. The design of experiment is the procedure of selecting the number of trials and conditions for running them, essential and sufficient for solving the problem that has been set with the required precision.

In general, the statistical method of design of experiment is based on a more sound logic than any other approach and helps in minimizing the time and the cost of experimentation and at the same time increases the authenticity of the results. Many latest techniques are available for experimental design which can be effectively used in scientific investigations of welding processes. One such important technique is Taguchi method for evaluating the effect of the parameters on the response.

Hence in the present work, this approach was selected for conducting the experiments and generating the data for predicting the effect of welding conditions on the bead geometry.

Development of Flux

In the present research work, agglomerated flux was developed for the welding of stainless steel (304) by submerged arc welding process.

The brief description of the steps of flux development is as follows:

Selection of Flux Ingredients

The selection of the flux constituents is based on the required physical properties of the flux and the chemical composition, mechanical properties of the weld metal. $CaO-SiO_2-MnO$ based flux was developed because of the ability to produce low oxygen content and hence to obtain superior mechanical properties. Calcium carbonate in place of calcium oxide was added due to the hygroscopic nature of the latter. Manganese oxide was added to increase the fluidity of the fluxes and to control the harmful effect of the sulphur in the weld metal. Aluminium oxide was added to refine the grains of the weld metal and to improve the detachability of the slag. Aluminium, ferrosilicon and titanium powders were added as deoxidizers. Ferro-manganese was added to meet the required weld metal manganese content. Potassium silicate binder was used due to its better arc stability characteristics than the sodium silicate. The composition of the developed flux is given in Table 1.

Flux Preparation

The flux ingredients were weighed as per the composition shown in the Table-1. These ingredients were dry mixed properly for 30 minutes so that the ingredients could form a homogeneous mixture. The solution of potassium silicate binder was added to wet the dry mixed powder and it was wet-mixed for 15 minutes and then passed through a 10-mesh screen to form small pellets. The pellets of the flux were mixed and dried separately in air for 24 hours and then were baked in the muffle furnace between 750-800^{o}C for nearly four hours. After cooling, these pellets were crushed and subsequently sieved. After sieving, fluxes were kept in airtight bags and used for welding.

Experimental Design

The experimental design was according to an orthogonal array (OA) based on the Taguchi method as the total degrees of freedom associated with the three parameters at three levels each (without interaction) is 7, which is less than 8, total degrees of freedom of L9 OA. The L9 orthogonal array had four columns and 9 rows, thus, four welding parameters can be apportioned to the columns and the rows designate nine experiments with various combination levels of the welding parameters. In this investigation only three welding parameters were considered, so one column was empty. The orthogonality is preserved, even if one column of the array remained empty. Three observed values of bead width and bead height were examined. The levels of each welding parameters were set in accordance with the L9 orthogonal array, based on the Taguchi experimental method. Moreover, the significant welding parameters associated with the bead width and bead height were determined by ANOVA based on S/N ratio.

Experimentation

The constant potential (flat characteristics) transformer-rectifier type power source with current capacity of 600 A and open circuit voltage ranging 12-48 volts was used. Fully mechanized submerged arc welding system of carriage type was employed to conduct the experiment. This machine also has the provision for controlling the wire feed rate and welding speed. DCEP polarity was used. The welds were laid by using 3.2 mm diameter wire and the laboratory made agglomerated fluxes. Welds were laid on the plates using bead on plate technique. The plates used for welding are of stainless steel 304 L grade. The process parameters and the range used for welding are given in Table 2. The chemical composition of the bead laid by using developed flux is given.

Table 1: Chemical Composition of the Flux

Type	Flux Ingredients (% by Wt.)						
	SiO_2 + Al_2O_3	CaO + CaF_2	MnO	Fe-Mn + Fe-Si	TiO_2	Al	Cr
Acidic	50	32	0.5	1.5	0.5	1	1.5

Table 2: Welding Parameters and Their Range

Parameter	Unit	Symbol	Level 1	Level 2	Level 3
Open Circuit Voltage	Volts	V	30	33	36
Current	Ampere	A	280	290	300
Travel Speed	m/hr	S	22	24	26

Analysis and Discussion

Analysis by Taguchi Method

The experiments were planned by using the parametric approach of the Taguchi's Method. The response characteristic data is provided in Table 3. The standard procedure to analyze the data based on S/N ratio, as suggested by Taguchi, is employed. The average values of the S/N Ratio of the quality/response characteristics for each parameter at different levels are calculated from experimental data. Both the response parameters viz. material removal and %age improvement in surface finish, are of "higher the better" type of machining quality characteristics, hence the S/N ratio for these types of responses is given below.

$$(S/N)_{HB} = 10.\log(MSD_{HB})$$

$$MSD_{HB} = \frac{1}{R}\sum_{j=1}^{R}\left(1/y_j^2\right)$$

Where R = Number of repetitions

y_j = Response value

The main effects of process parameters for S/N Ratio for each response are plotted by calculating the average values of response characteristics for each parameter at level one, level two and level three (L1, L2, L3). The analysis of variance (ANOVA) of S/N Ratio data is performed to identify the significant parameters and to quantify their effect on the response characteristics.

Effect on Bead Height

The average values and main effect (S\N Data) of current, voltage and travel speed on bead height are shown in figure 1, 2 and 3 respectively. Tables 4 and 5 shows the results of ANOVA for Raw Data and S/N Ratio associated with bead height obtained from the L_9 orthogonal array based on Taguchi method.

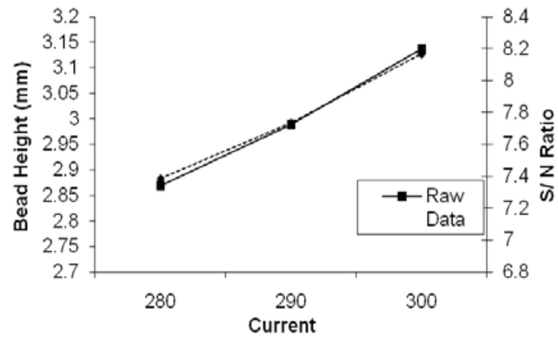

Fig. 1: Effect of Current on Bead Height

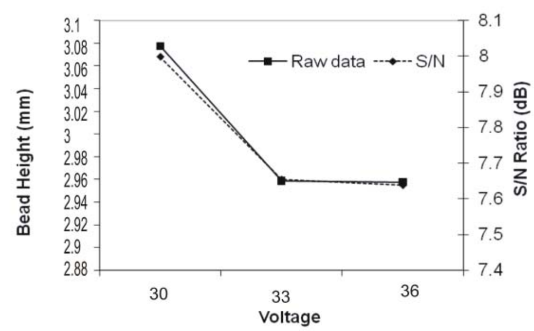

Fig. 2: Effect of Voltage on Bead Height

Table 3: The L_9 (3^4) OA with Experimental Results of Various Response Characteristics

Exp No.	Run Order	Parameter Conditions				Responses for Bead Height(mm)				Responses for Bead width(mm)			
		1	2	3	4	Raw Data for Bead Height (mm)			S/N Ratio (dB)	Raw Data for Bead Width (mm)			S/N Ratio (dB)
		A	V	S	e	R_1	R_2	R_3		R_1	R_2	R_3	
1	1	1	1	1	1	2.96	2.92	2.98	7.64	16.78	16.98	16.71	22.75
2	3	1	2	2	2	2.85	2.9	2.87	7.40	17.93	17.07	17.67	23.12
3	2	1	3	3	3	2.78	2.87	2.69	7.11	17.96	17.87	18.01	23.31
4	4	2	1	2	3	3.127	3.09	3.15	8.12	15.72	16.07	16.15	22.30
5	6	2	2	3	1	2.91	2.83	3	7.51	16.76	16.83	16.86	22.75
6	5	2	3	1	2	2.93	2.81	3.05	7.56	18.64	18.57	18.65	23.63
7	9	3	1	3	2	3.21	3.09	3.17	8.22	15.27	14.99	15.27	21.86
8	7	3	2	1	3	3.09	3.05	3.13	8.03	18.02	17.39	17.33	23.13
9	8	3	3	2	1	3.15	3.19	3.15	8.24	17.92	17.99	17.85	23.30
Total						**27.00**	**26.75**	**27.19**		**155**	**153.76**	**154.5**	
						Overall mean of Bead Height = 2.99mm				Overall mean of Bead Width = 17.15mm			

R1, R2, R3 represent response value for three repetitions of each trial. The 1's, 2's, and 3's represent levels 1, 2, and 3 of the parameters. (e) represents no assignment in the column.

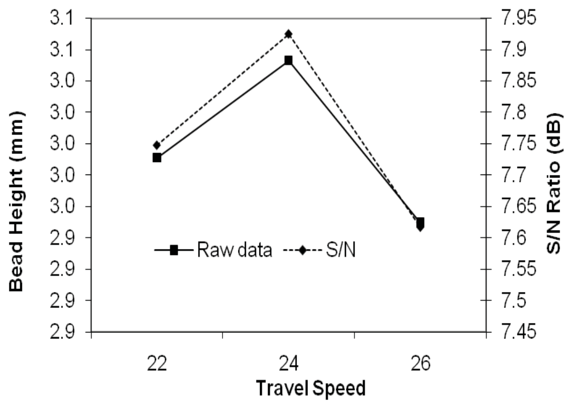

Fig. 3: Effect of Travel Speed on Bead Height

As shown in the table 4 and 5, all the selected three parameters of current (A), voltage (V) and travel speed (S) significantly affect both the mean and the variation in the bead height values. The percentage contribution of current is highest (60.42%) for bead height followed by voltage (15.88%), and travel speed (9.02%).

Table 4: ANOVA (Raw Data, Bead Height)

Source	SS	DOF	V	P%	F-Ratio
A	0.32	2	0.161	60.42	41.19*
V	0.085	2	0.042	15.88	10.82*
S	0.048	2	0.024	9.02	6.15*
e	-	-	-	-	-
ERROR	0.078	20	0.003	14.66	
Total (T)	0.53	26	-	100	

* Significant at 95 % confidence level. Fcritical=3.4928
SS –Sum of Squares, DOF–Degree of Freedom, V–Variance

Table 5: ANOVA (S/N Ratio, Bead Height)

Source	SS	DOF	V	P%	F-Ratio
A	0.91	2	0.45	69.60	114.88*
V	0.24	2	0.123	18.84	31.10*
S	0.143	2	0.07	10.94	18.05*
e	-	-	-	-	-
ERROR	0.007	2	0.003	0.60	
Total (T)	1.312	8	-	100	

* Significant at 95 % confidence level. Fcritical=19
SS –Sum of Squares, DOF–Degree of Freedom, V–Variance

It is evident that bead height increases with increase in current. As the current increases, heat input per unit time and the weight of wire fused and deposited per unit time increases. Therefore the size of the weld pool increases which lead to increase in bead height. Increase in voltage leads to decrease in bead height. As the increase in voltage results in increase in the arc length, arc voltage and heat input. The increase in the heat input results in increase in penetration. The marginal increase in the heat input and the metal deposition rate are utilized for increasing the value of penetration and so the bead height decreases with increase in voltage. Bead height decreases with increase in travel speed, because of the welding torch travelling at high speed over the base metal upon increase in travel speed. This increase in torch speed leads to lesser metal deposition rate on the bead. Also the increase in travel speed reduces the heat input and hence the weight of base metal melted. Because of less heat input and a lesser metal deposition rate, the size of weld pool reduces and hence bead height reduces with increase in travel speed.

The optimum levels of the parameters for the higher bead height are the third level of current (A_3), first level of voltage (V_1) and second level of travel speed (S_3).

Effect on Bead Width

The average values and main effect (S\N Data) of current, voltage and travel speed on bead width are shown in figure 4, 5 and 6 respectively. Tables 6 and 7 shows the results of ANOVA for Raw Data and S/N Ratio associated with bead width obtained from the L_9 orthogonal array based on Taguchi method.

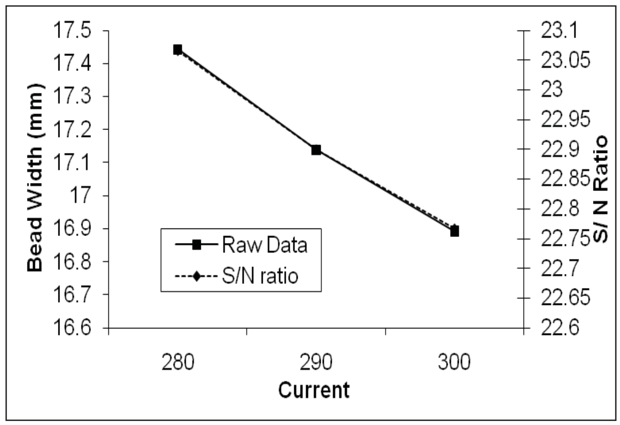

Fig. 4: Effect of Current on Bead Width

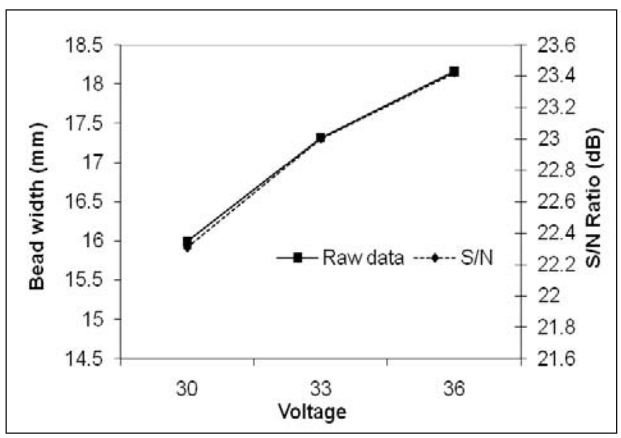

Fig. 5: Effect of Voltage on Bead Width

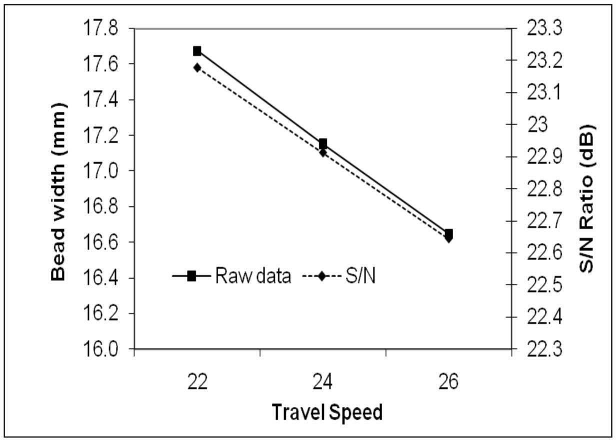

Fig. 6: Effect of Travel Speed on Bead Width

Table 6: ANOVA (Raw Data, Bead Width)

Source	SS	DOF	V	P%	F-Ratio
A	1.36	2	0.683	4.78	14.69*
V	21.51	2	10.75	75.32	231.49*
S	4.75	2	2.37	16.64	51.15*
E	-	-	-	-	-
ERROR	0.92	20	0.046	3.25	
Total (T)	28.56	26	-	100	

*Significant at 95 % confidence level. Fcritical=3.4928
SS –Sum of Squares, DOF–Degree of Freedom, V–Variance

As shown in the table 6 and 7, all the selected three parameters of current (A), voltage (V) and travel speed (S) significantly affect both the mean and the variation in the bead width values. The percentage contribution of voltage is highest (75.32%) for bead width followed by travel speed (16.64%), and current (4.78%).

It is evident that the bead width decreases with increase in current. As the current increases, heat input per unit time and the weight of wire fused and deposited per unit time increases. Therefore the size of the weld pool and bead height increases. Because of which the value of bead width decreases.

Table 7: ANOVA (S/N Ratio, Bead width)

SOURCE	SS	DOF	V	P%	F-Ratio
A	0.134	2	0.067	5.45	20.10*
V	1.89	2	0.94	76.99	283.95*
S	0.42	2	0.21	17.28	63.73*
e	-	-	-	-	-
ERROR	0.006	2	0.003	0.27	
Total (T)	2.45	8	-	100	

*Significant at 95 % confidence level. Fcritical=19
SS –Sum of Squares, DOF–Degree of Freedom, V–Variance

The bead width, increase with increase in voltage, because of the increase in voltage results in increase in the arc length, arc voltage and heat input. The increase in the arc length results in the spreading of arc cone at its base which leads to an increase in bead width. Bead width decreases with increase in travel speed, because of the welding torch travelling at high speed over the base metal when travel speed is increased. This increase in torch speed leads to lesser metal deposition rate on the bead. Also the increase in travel speed reduces the heat input and hence the weight of base metal melted. Because of less heat input and a lesser metal deposition rate, the size of weld pool reduces and hence the bead width reduces with increase in welding speed.

The optimum levels of the parameters for the higher bead width are the first level of current (A_1), third level of voltage (V_3) and first level of travel speed (S_1).

Conclusion

1. All the selected three parameters of current (A), voltage (V) and travel speed (S) significantly affect both the bead height and bead width.
2. With the increase in welding current, bead height increases but the bead with decreases.
3. Bead height decreases with the increase in welding open circuit voltage, but the bead width increases.
4. As the travel speed increases both the bead height and bead width decreases.

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